

Appendix F

NAVIGATION USING GPS

Since GPS is a primary candidate to support the crash location function, this appendix examines its use in an ACN system. After a brief description of GPS, system availability and accuracy issues are discussed.

F.1 GLOBAL POSITIONING SYSTEM OPERATION

The NAVSTAR Global Positioning System is a satellite-based radio navigation system that was developed and is currently operated by the DOD. It provides near continuous three-dimensional position, velocity, and time information globally. It is composed of three segments. The space segment consists of 24 satellites in 12-hour orbits at an altitude of 10,898 nmi. The satellites are divided into six orbital planes with four satellites in each plane. The control segment is the ground control system that monitors and controls system operation. The user segment is composed of the GPS receivers. This section summarizes GPS operation. Additional detail can be obtained from Reference F-1.

Location estimates are calculated using passive ranging in which the receiver determines the range to a satellite by measuring the time required for a signal to propagate from the satellite to the receiver. A single range estimate, known as a pseudorange, then defines a sphere around the satellite upon which the receiver must reside. However, to determine a unique three-dimensional position (latitude, longitude, and altitude), the ranging information from a single satellite is not sufficient. Similar information from at least two other satellites must be obtained. Furthermore, due to lack of clock synchronization, a fourth satellite must be tracked to solve for the clock bias. (This changes pseudoranges to actual ranges). Time must always be determined before position can be determined. The space segment is designed to keep at least six satellites in view at all times from any position on earth. However, vehicles in canyons, tunnels, densely forested areas, or cities may have line-of-sight to one or more satellites blocked. If less than four satellites are visible, a position solution may not be possible and the receiver will lose lock. On the other hand, if altitude can be determined by some other means, only three satellites are needed. For example, some receivers estimate current altitude from a previous (recent) altitude determination.

The GPS system measures signal propagation time by using pseudonoise (PN) codes. The start or epoch of each code is synchronized for the entire satellite constellation. The receivers determine time delay by measuring the shift in the epoch of each code. Since each satellite is assigned a different code and the codes have low cross-correlation properties, they can be transmitted at the same frequency. Two-types of PN

codes are used. One is a clear acquisition (C/A), code and the other is a precision (P) code. The C/A code is never encrypted (clear) and is used to enable the acquisition of P code in P code receivers. The C/A code is transmitted at a 1.023 Mchip/sec rate and repeats every millisecond. The P code is transmitted at 10.23 Mchip/sec and repeats every week. Because P code is ten times the rate, it is that much more accurate. Although P code receivers are available to commercial users, the military can encrypt the P code, then known as Y code, so that only authorized military receivers can decode the signal. Most commercial GPS receivers are C/A code only receivers. Commercial P code receivers are expensive and generally used in surveying applications.

The DoD decided the C/A code was too accurate for unrestricted and potentially hostile use. To degrade accuracy for open use and still retain high accuracy for authorized use, the DoD has employed a technique referred to as selective availability (SA). This involves intentionally dithering the C/A code clock and the ephemeris. Both cause the satellite to appear in a different position than it truly is. These effects can be removed by military users with the appropriate cryptographic keying information.

GPS satellites transmit the C/A code and P code in phase quadrature at a center frequency of 1575.42 MHz (known as L1). The waveform is described by Equation F-1:

$$s(t) = p(t) d(t) \cos \omega_c t + 2 c_a(t) d(t) \sin \omega_c t \quad (F-1)$$

where:

$$\begin{aligned} p(t) &= \text{P code} \\ c_a(t) &= \text{C/A code} \\ d(t) &= \text{navigation data} \end{aligned}$$

The satellites also transmit the P code only at a center frequency of 1227.6 MHz (known as L2). For systems requiring high accuracy, reception of the two frequencies allows ionospheric delays to be estimated and corrections made to the signal propagation times.

For a receiver to determine its range from the satellite, it must know the position of the satellite and the time when the signal was sent. The navigation data stream, $d(t)$, provides this information to the receiver. It includes satellite ephemeris parameters (orbital characteristics), almanac data (visible satellites), age of the data, satellite clock correction coefficients, etc. These data occupy 25 data frames that consist of 1500 bits per frame. At 50 bits per second, an entire download of navigation data requires 12.5 minutes. Fortunately, it is possible to calculate position without downloading the entire message because the almanac data do not change very often and can be stored in the receiver.

The process of acquiring code-lock with GPS satellites can take several minutes due to uncertainty in time (the code correlation process) and frequency (e.g., Doppler shift, receiver frequency standard drift) and downloading of the navigation information. However, multi-channel receivers can reduce acquisition time by performing

correlations simultaneously. Typical times to first fix assuming warm start (clock is warmed up) and good almanac (which provides estimates of Doppler shift) are listed below:

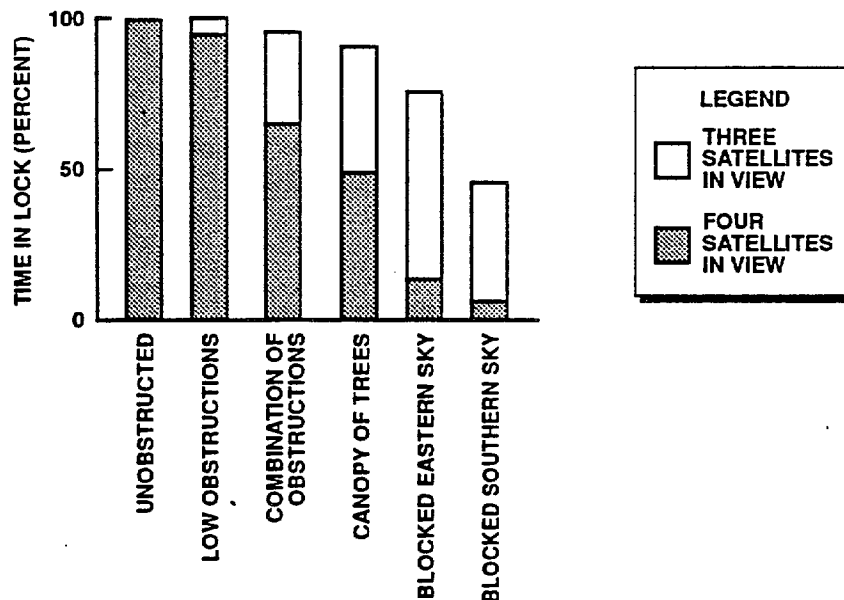
| | |
|--------------------|-------------|
| 1 channel receiver | 4 minutes |
| 2 channel receiver | 3 minutes |
| 5 channel receiver | 1.5 minutes |

The long acquisition times imply that a GPS receiver should begin operating when the vehicle is first started instead of when the vehicle crashes.

F.2 AVAILABILITY

Based on the discussion in Section F.1, it is necessary for a GPS receiver to have at least four satellites in view to estimate location assuming that no additional side information is available. If side information, such as receiver altitude, is available, only three satellites are necessary for a position fix. Therefore, as long as three satellites are in view, the receiver is available to estimate its location (and the receiver is considered in lock). Unfortunately, it is not always possible to keep three satellites in view. For example, in a city or a mountainous region, GPS timing signals can be blocked by buildings or terrain irregularities, respectively. Also, in rural areas, dense foliage near the roadway may attenuate signal power below usable levels. To examine the effect of signal blockage on receiver availability, location estimates were taken for several different obstruction scenarios. Data were collected at 20-second intervals for periods ranging from 16 to 30 hours. The results are presented in Figure F-1. This figure summarizes the percentage of time three and four satellites are in view for a variety of obstruction scenarios.

For the unobstructed case, the receiver's antenna was placed on top of a 50-ft tall building, which provided an unobstructed view of all satellites in the constellation that were a few degrees above the earth's horizon. At least four satellites were available at all times. By moving the receiver to a location with low obstructions, the percentage of time four satellites are in view drops to 95% but the receiver is still able to continue to operate with three satellites. The obstructions consist of a mixture of buildings and trees that encircle the receiver antenna. They typically blocked up to 20 degrees in elevation angle. Since low obstructions did not affect availability significantly, data were collected for a scenario in which the receiver antenna was blocked by a combination of low and high obstructions (blocking 0 to 90 degrees in elevation angle and 180 degrees in azimuth). The low obstructions were composed of a mixture of buildings and trees, whereas the high obstructions were trees only. The figure indicates that tall trees have significantly increased the amount of time only three satellites are available. Furthermore, 5% of the time, the receiver is out of lock. To further increase the effect of foliage obstructions, the receiver antenna was placed under a canopy of trees; that is, nearly hemispherical blockage. The trees were deciduous (with full foliage) and ranged in height from 30 to 60 feet. Both the amount of time three satellites are in view and the amount of time the receiver is out of lock have increased. Less than 50% of the time, four satellites are in view.



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Figure F-1 GPS Availability

To examine the effects of signal blockage by a building (or an equivalent terrain feature such as a rock outcropping in a mountainous region), receiver availability data were taken from a location in which a building obstructs the view to all satellites in half of the sky. An eastern blockage scenario and a southern blockage scenario were examined. It is clear that this type of blockage impacts availability significantly. Four satellites are in view less than 15% of the time. Furthermore, the data for the case where the southern sky was blocked indicates that availability was less than 50%. Note that the difference between the availability for the two blockage scenarios results from poorer satellite geometry.

Figure F-1 implies that since the receiver may not be available to make location estimates constantly, it is advisable to obtain position estimates while the vehicle is operating instead of waiting until the crash occurs. Also, it is important to consider the receiver output during loss of lock. In the test receiver case, the receiver outputs the last position fix and provides an indication of out of lock.

F.3 ACCURACY

There are several sources of error that degrade the accuracy of location estimates produced by a commercial C/A code GPS receiver. These include propagation anomalies, poor satellite geometry, and SA (which is the largest source of error). With SA operating, a GPS receiver's accuracy is specified to be better than 100 meters 95% of the time assuming that the receiver's antenna has an unobstructed view of the available satellites.

However, it is not clear how accuracy-degrades-when satellites are blocked. This section examines the accuracy of the GPS receiver position fixes for each of the cases discussed in Section F.2.

Figure F-2a shows a plot of the variation of location estimates, taken once every 20 seconds over a 17-hour period, when a receiver has an unobstructed view of all available satellites. The variations rarely exceed 200 meters. This is illustrated more quantitatively in Figure F-2b, which shows the distribution of the variations. Variations greater than 100 meters occur approximately 5% of the time. The high degree of accuracy would permit EMS personnel to rapidly locate crash victims even in poor conditions such as inclement weather and at night.

Figure F-3 illustrates the effects of low obstructions on location accuracy. From both the plot of location estimates and the distribution function, it is clear that the obstructions have not degraded receiver accuracy significantly. Note that the accuracy was not affected, even though only three satellites were visible 5% of the time.

Figure F-4 indicates that although low obstructions do not degradereceiver performance, the combination of tall trees with the low obstructions does.. The amount of time the variations are less than 100 meters has decreased from 95% to 83%. Furthermore, there are periods when the magnitude of the variations exceeds 1 kilometer (out to a maximum of 3 kilometers). However, the excursions tend to have short durations. These occurred less than 1% of the time. It is expected that the peak variations can be correlated with satellite geometry and location of tree trunks. Note that the error distributions shown in Figures F-4 through F-7 account only for periods when the receiver is in lock. (Receiver availability was 100% for data in Figures F-2 and F-3.) Therefore, to calculate percentage of total time the receiver estimates were better than 100 meters, it is necessary to multiply the receiver availability values in Figure F-1 by the percentage of time the errors are below 100 meters in Figures F-4 through F-7. For this example, the total time the receiver estimate was better than 100 meters is $0.95 \times 0.87 = 0.83$. Also, the total time the receiver estimate was worse than 100 meters or was out of lock was 17%.

The impact of operating under a canopy of trees on estimate variation is shown in Figure,F-5. In this case, the amount of time the variations were below 100 meters is 73%. Also, like the previous figure, there are excursions well over 1 kilometer.

Figure F-6 shows the effect on accuracy of a building blocking the eastern half of the sky. Figure F-6a indicates that the maximum variation is similar to that generated by the overhead trees. However, Figure F-6b shows that the amount of time the variations are less than 100 meters has decreased to 45%. The increase in variability over the overhead foliage case -verifies that usable signals are able to pass through the foliage while the building casts a radio frequency shadow at 1575 MHz.

In Figure F-6, the large variations tend to have an east-west orientation. This is as expected since the obstruction runs north-to-south, and thus, the remaining satellite geometry makes an accurate east-west determination difficult. To verify this

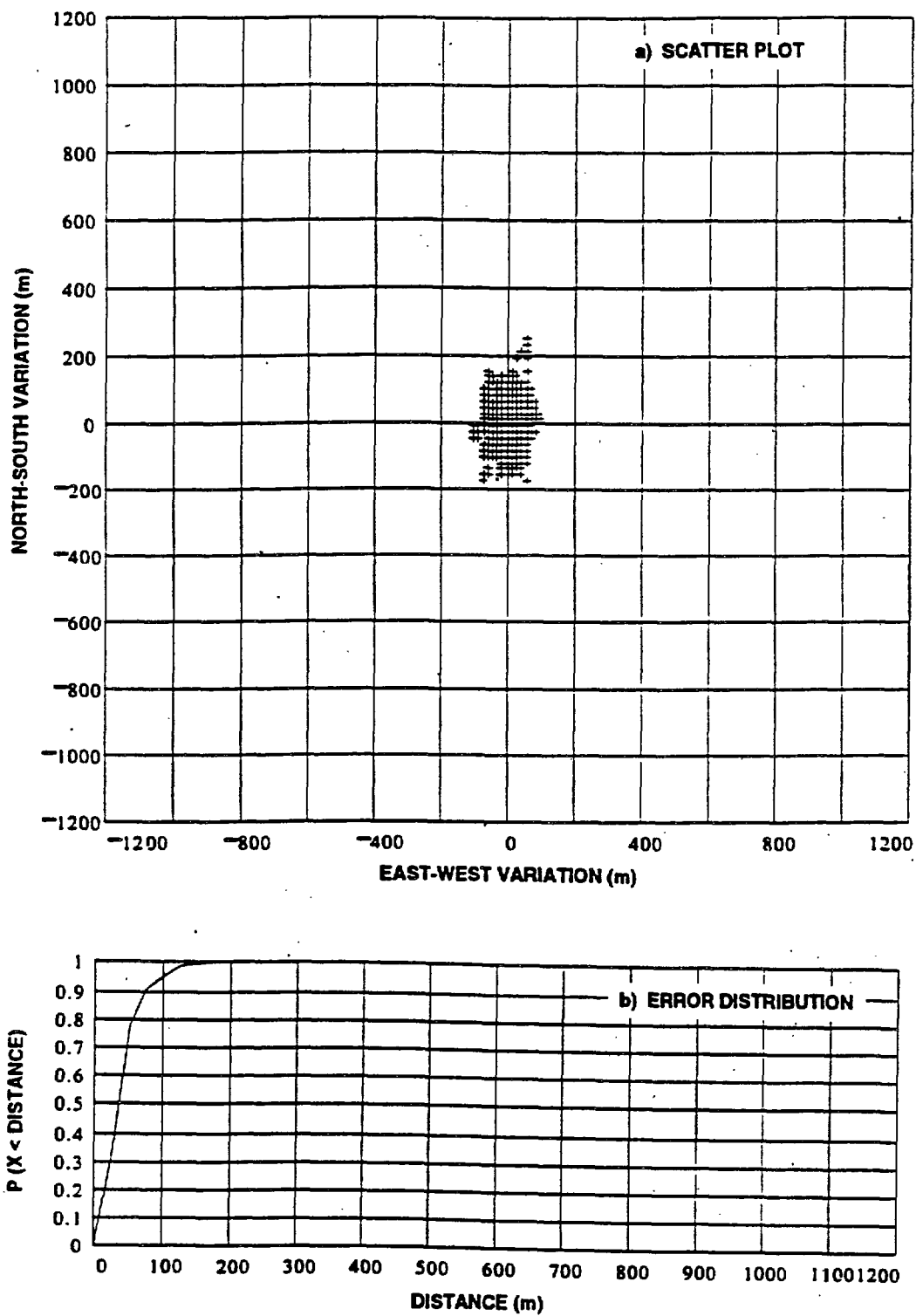


Figure F-2 GPS Accuracy with Unobstructed View of Available Satellite

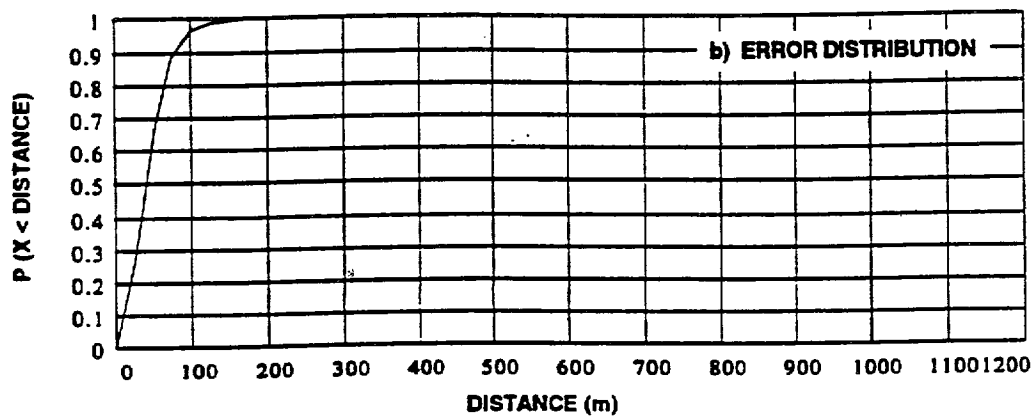
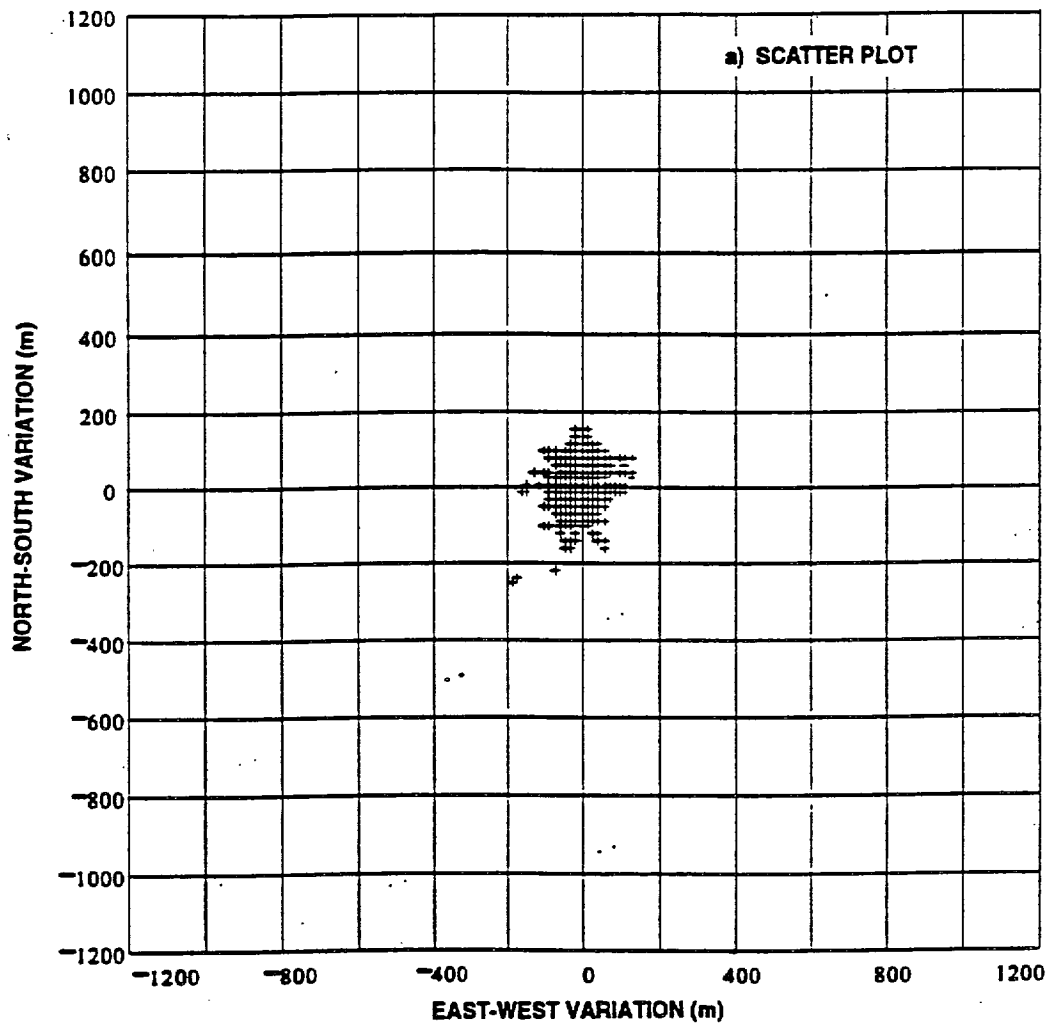


Figure F-3 GPS Accuracy with Low Obstructions

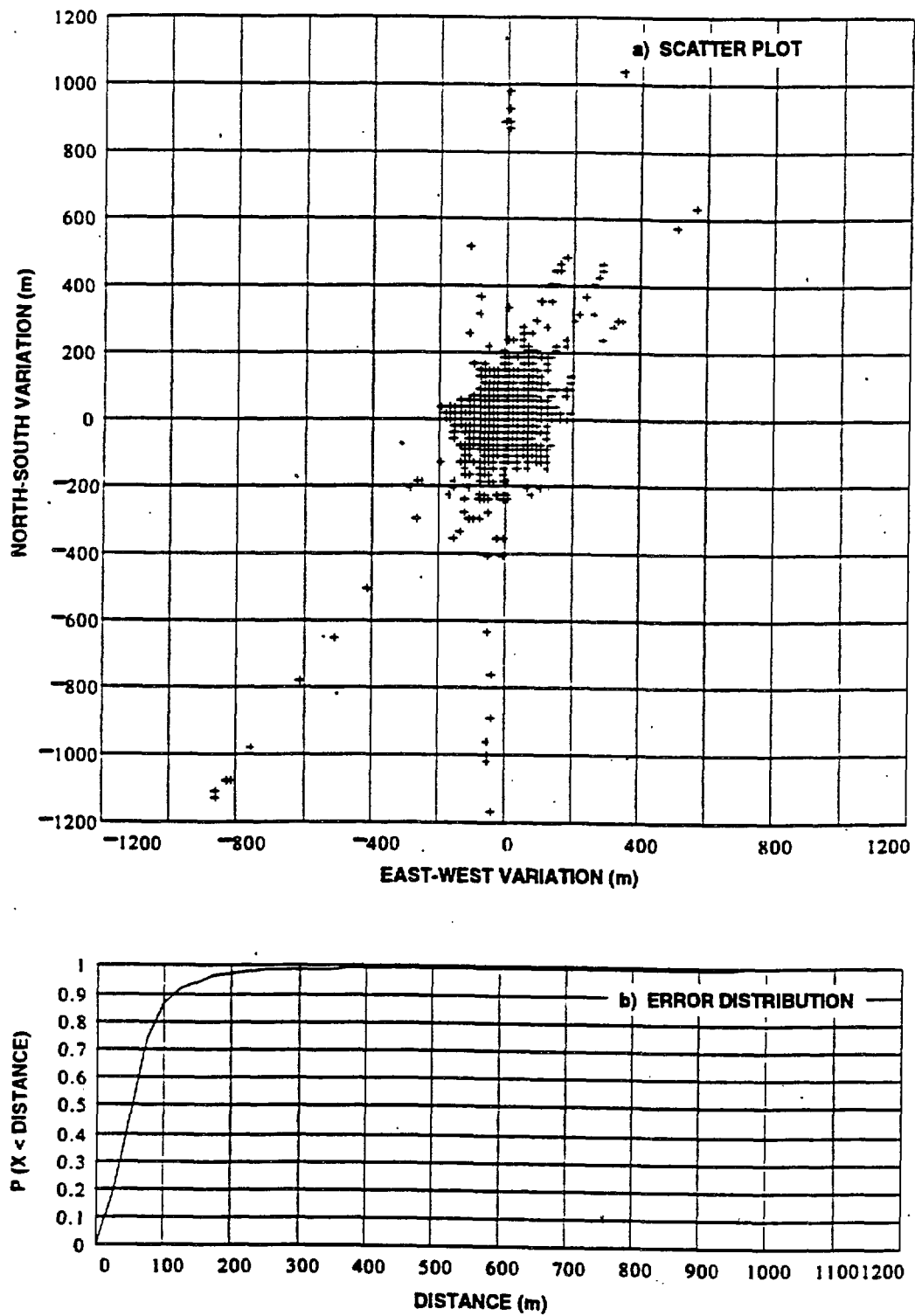


Figure F-4 GPS Accuracy with a Combination of Obstructions

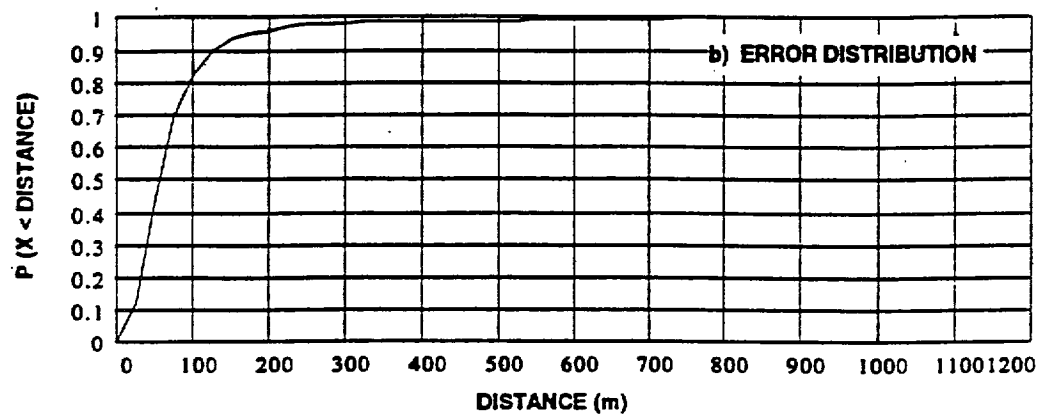
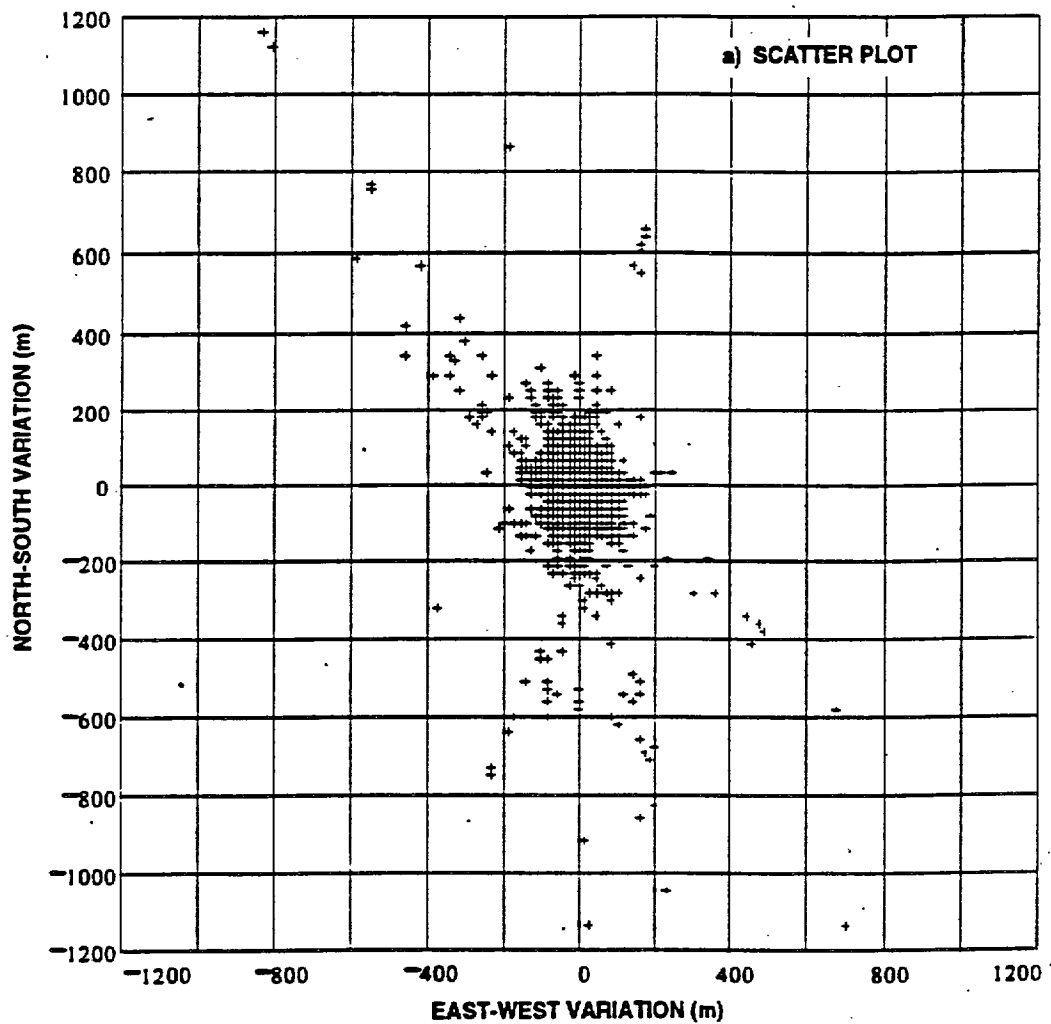


Figure F-5 GPS Accuracy When Operating Under a Canopy of Trees

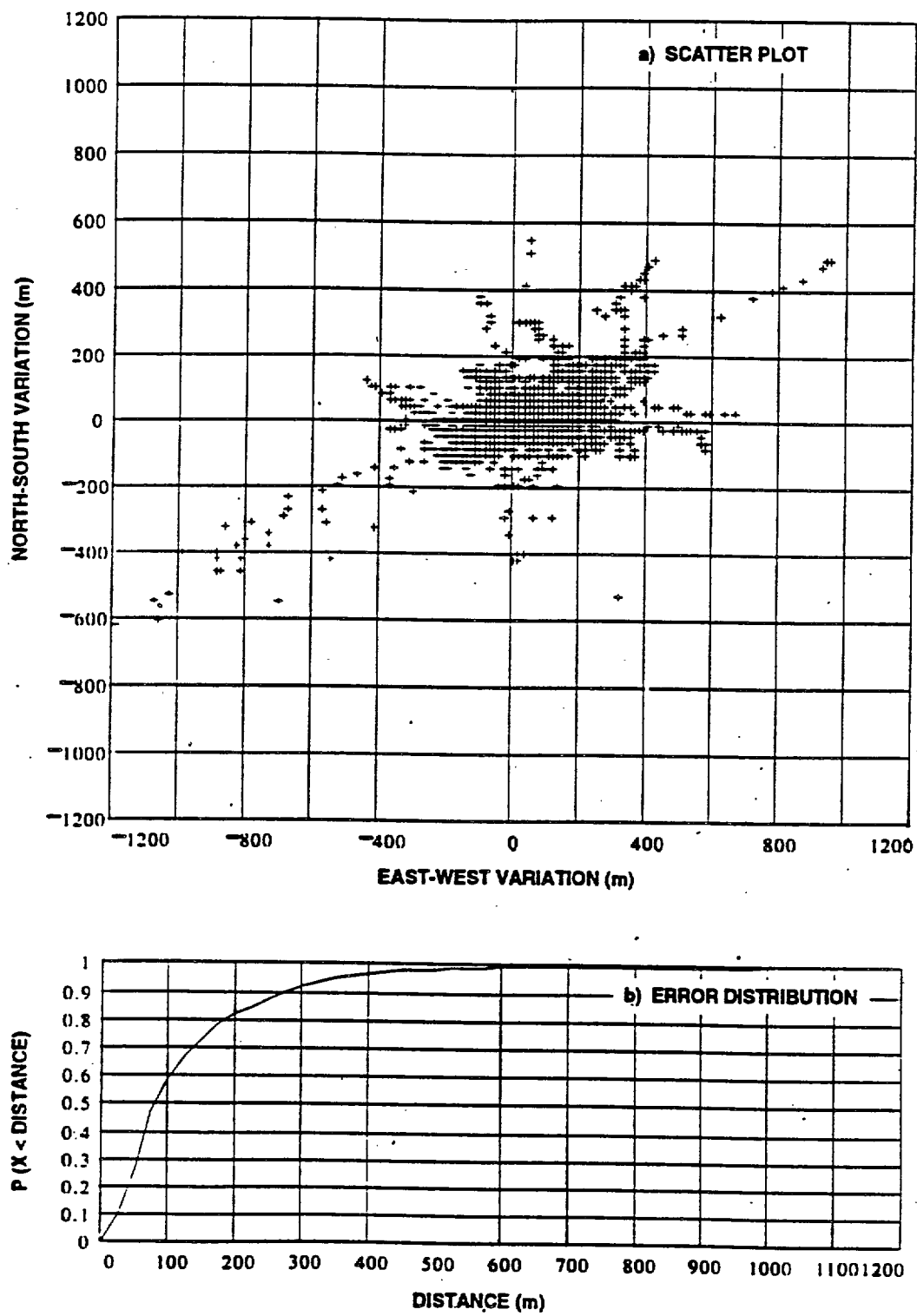


Figure F-6 GPS Accuracy with Eastern Sky Blocked

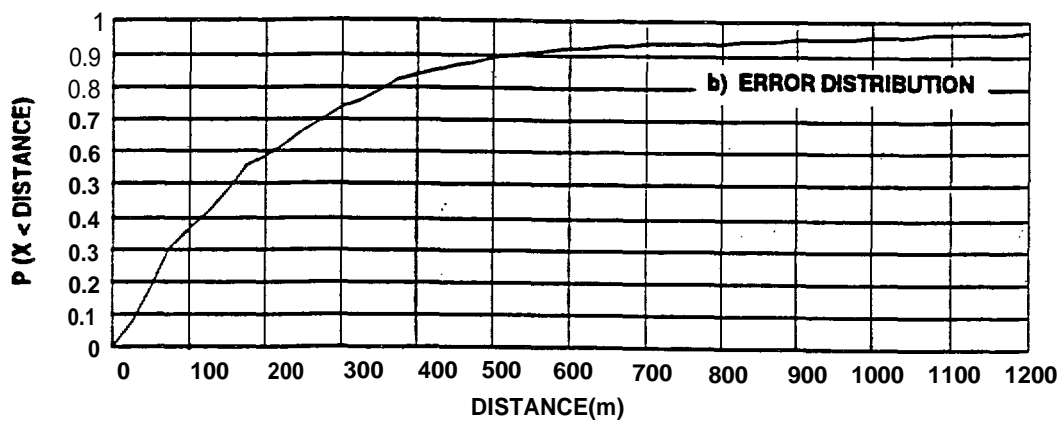
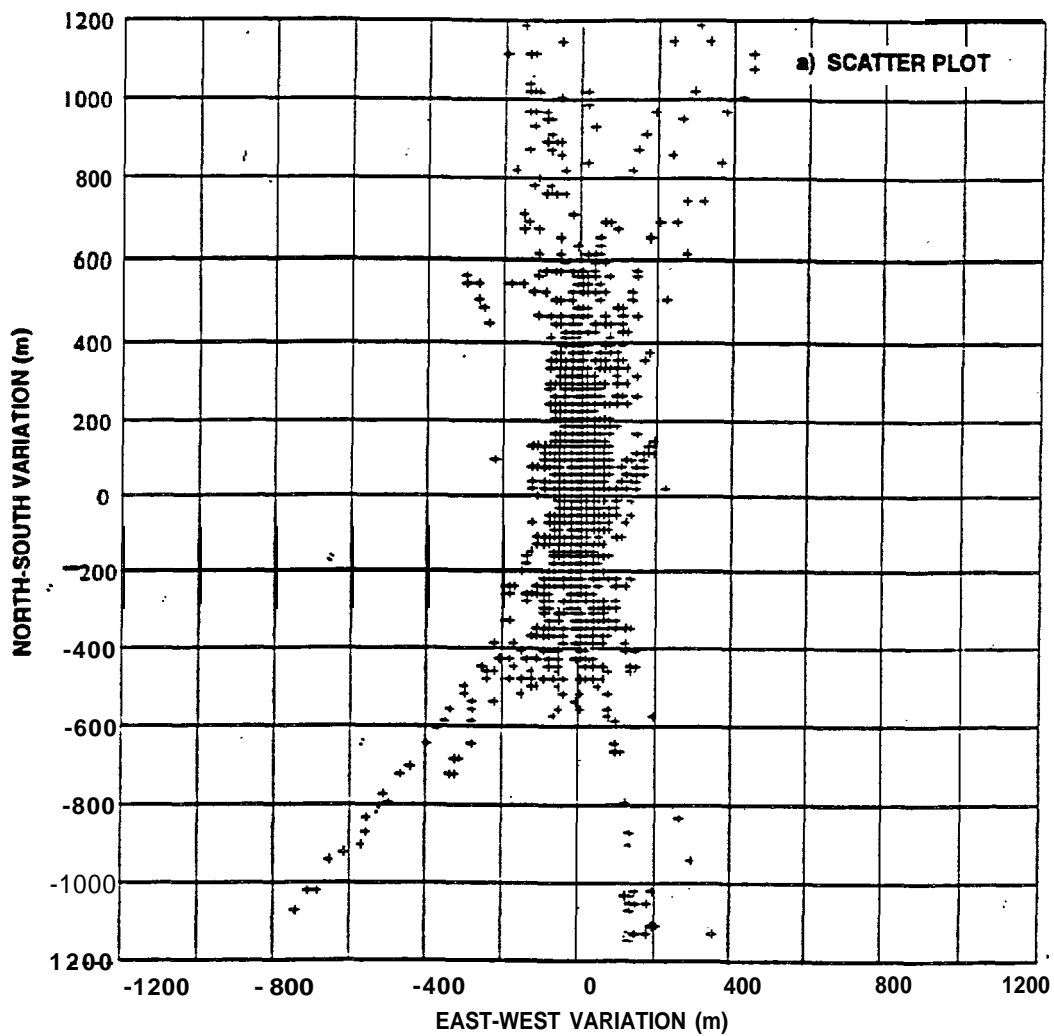


Figure F-7 GPS Accuracy with Southern Sky Blocked

relationship, data from the southern half of the sky blockage was also examined. Figure F-7 indicates a similar relationship. In this case, the large variations are oriented north-south. Note that Figure F-7b shows a substantial increase (over the data described in Figure F-6) in the amount of time the variations are greater than 100 meters. Furthermore, almost 5% of the time, the variations are greater than 1 kilometer. Based on Figures F-6 and F-7, it is expected that worst-case inaccuracies would occur in areas where terrain shadowing is significant, such as mountainous regions.

F.4 ERROR

Since it is possible for GPS receiver location estimates to be more than 1 kilometer in error or even unavailable for significant periods, it is desirable to provide EMS personnel with an indication of decreased accuracy. One method that could be employed is the use of the error estimate generated by the receiver. The estimate attempts to account for a variety of error sources including the use of suboptimal satellite geometries (dilution of precision) and satellite range errors from SA. Figure F-8 shows the error estimate compared to the actual error. There was no obstruction of satellites. Figure F-8a is the predicted error. Figure F-8b is the actual error. Figure F-8c indicates that the receiver was always able to obtain a position fix while Figure F-8d shows the difference between the predicted and actual error. Although there are two instances where an actual error occurred and there was a corresponding increase in predicted error (at sample count 400 and 8000), in general, the predicted error does not appear to correlate well with the actual error. Also, it tends to greatly overestimate the error. Less promising results are shown in Figure F-9, which is taken from the tree canopy obstructed data. Almost every time there was a large actual error, there was a large predicted error. But the predicted error was often large when the actual error was not. Thus, the predicted error is more of an upper bound than an accurate prediction. Note that the receiver limits the predicted error to 1 kilometer.

Figures F-8 and F-9 indicate that the receiver's error estimate is an upper bound. This implies that the estimate cannot be used to predict the error magnitude. However, it can be used to predict when a position fix is reliable. When the error is predicted to be low, it is expected that the location accuracy is high. This information combined with an out-of-lock indication and a time from last reliable position fix would provide EMS dispatchers with valuable reliability information. Furthermore, the information could be used by a dead reckoning system in the vehicle to estimate location when blockage of satellites occur. Dead-reckoning systems estimate location by tracking distance traveled and heading changes. Highly accurate location estimates could be obtained with a hybrid GPS and dead-reckoning system, but the cost would be higher than a GPS-only system.

Two other methods that can address errors resulting from obstructions are differential navigation and a device developed by NAVSYS Corporation called the Tidget. Both methods are described in Section 5. Differential navigation can improve position accuracy by approximately a factor of 10. Thus, errors of 100 meters would be reduced to 10 meters, but more importantly, errors of 1000 meters would be reduced to 100 meters. This would allow almost any position fix that occurred near the time of a crash to be used with certainty. The only source of significant errors would then be from loss of lock which

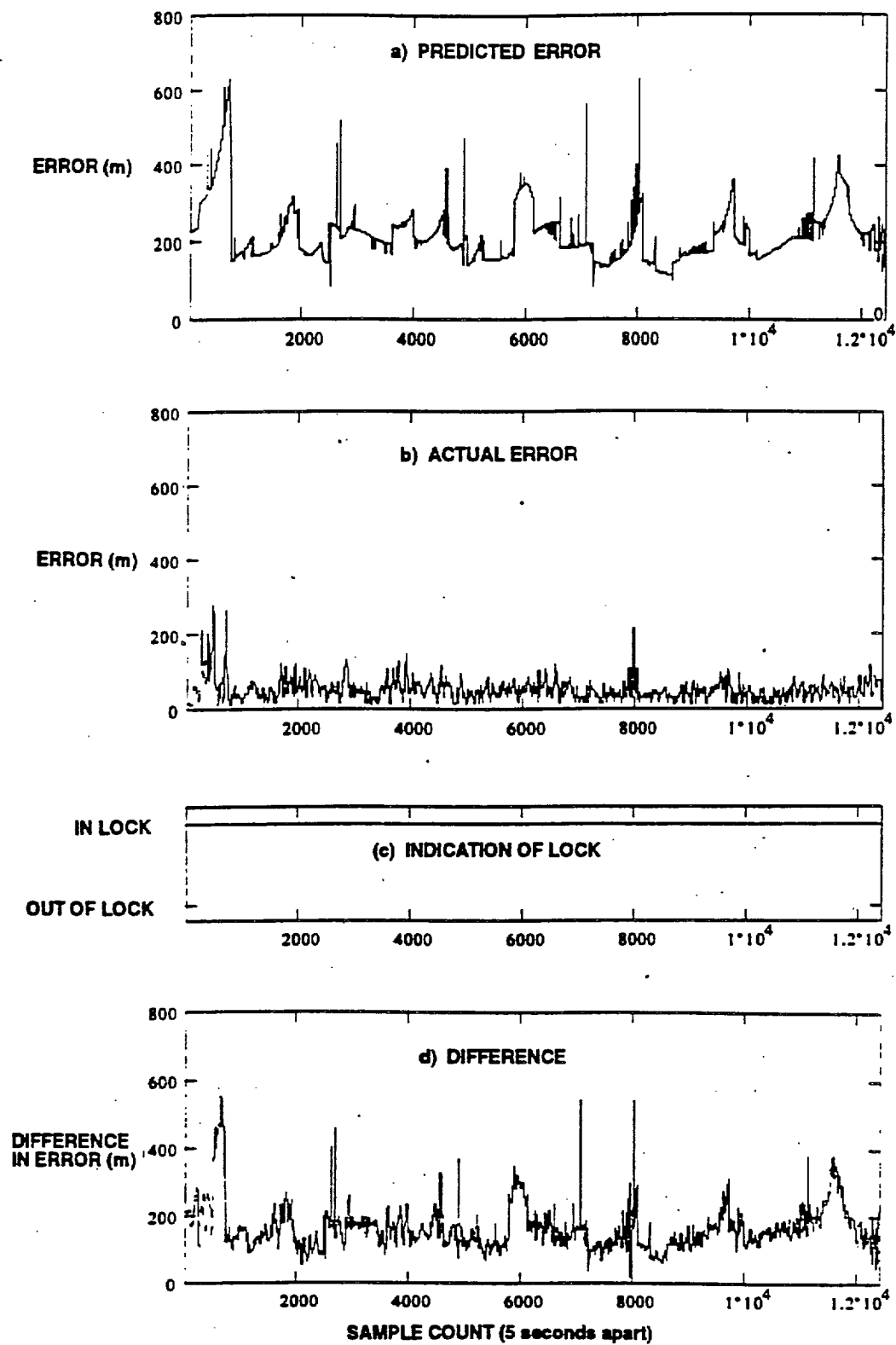


Figure F-8 Comparison of Error When GPS Receiver Has An Unobstructed View

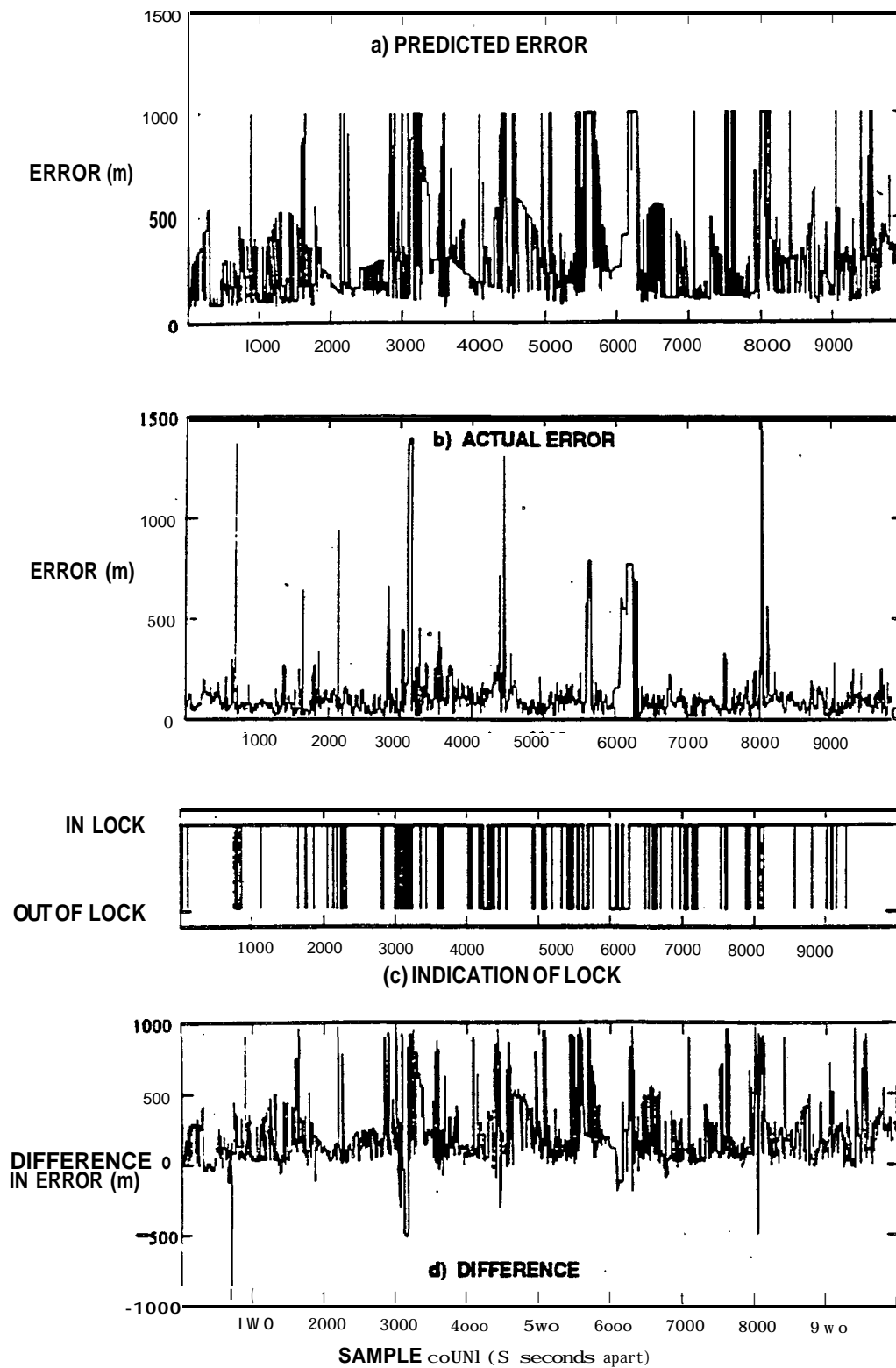


Figure F-9 Comparison of Error When GPS Receiver Operates Under a Canopy of Trees

could be minimized by dead reckoning. The primary issues associated with this technique are the availability of a differential correction signal and the increase in system cost resulting from requiring a differential receiver.

NAVSYS claims that Tidget can take advantage of knowledge of road locations and topographic information to decrease the number of satellites that must be visible to two. However, it is unclear how effective Tidget is if the vehicle is not on the roadway. A final technique to consider is relative navigation. This is similar to differential navigation, but does not require a differential receiver in the vehicle. The crashed vehicle transmits its position estimate and a list of which satellites were used in making that estimate and the time of the estimate. The local dispatch facility must maintain a short list of satellite pseudoranges from a local antenna at a known position. Upon receipt of the vehicle's message, the dispatch facility forms a navigation solution based on the pseudoranges from the same time and satellites as those used by the vehicle. This produces a position estimate with the same errors as those in the vehicle's estimate. The error from the true position of the dispatch antenna can then be subtracted from the vehicle's position to produce a more accurate position for the vehicle. Out-of-lock conditions would still require dead reckoning to minimize their impact.

F.5 SUMMARY

Position fixes made by a GPS receiver were collected for a variety of satellite obstruction scenarios to examine the accuracy and availability of a GPS location estimate. The data indicate that it is possible for foliage and terrain to induce errors with considerable magnitude. In some cases, variations of the position estimate were greater than 1 kilometer. Furthermore, there can be periods when the receiver is not able to acquire enough GPS satellites to allow it to make a position fix. Therefore, it is important for EMS personnel responding to a crash to be aware of the possibility of decreased location accuracy. There are several techniques that could assist the EMS dispatcher in predicting or reducing the error, but additional analysis to determine effectiveness is required in some cases, including relative navigation. Without mitigation of errors caused by obstructions, other location estimating techniques become more attractive, such as Loran-C that operates in the very low frequency band. Signals propagating in this band are not as sensitive to obstructions as GPS signals.

REFERENCES

F-1. "A GPS Primer," Corrigan T. M., JHIJ/APL Report